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Technical Memorandum

A Rho-cee Hydrophone

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14. ABSTRACT
Traditional piezoelectric materials have much higher impedances than water, and so most hydrophones are hard compared to the surrounding water medium. This "hardness" is the cause of internal and external reflections which manifest themselves as resonance and diffraction factor effects, respectively. Even nonvoided polyvinylidene fluoride (PVDF), a piezoelectic polymer, has a characteristic acoustic impedance (pc) about 2.5 times that of water. With the advent of voided PVDF, however, it is possible to match water's impedance as closely as desired. Through the use of pc window material and)pc PVDF, we have constructed a pc hydrophone whose response is essentially free of resonance and diffraction factor effects.

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ABSTRACT

Traditional piezoelectric materials have much higher impedances than water, and so most hydrophones are hard compared to the surrounding water medium. This "hardness" is the cause of internal and external reflections which manifest themselves as resonance and diffraction factor effects, respectively. Even nonvoided polyvinylidene fluoride (PVDF), a piezoelectic polymer, has a characteristic acoustic impedance (ρc) about 2.5 times that of water. With the advent of voided PVDF, however, it is possible to match water's impedance as closely as desired. Through the use of ρc window material and ρc PVDF, we have constructed a ρc hydrophone whose response is essentially free of resonance and diffraction factor effects. [Work supported by Naval Material Command via NUSC's Independent Exploratory Development program.]

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This memorandum was prepared under Job Order No. A61404, "Broadband Hydrophone for Transient Measurements," Principal Investigator: Dr. M. B. Moffett, Code 3321, Associate Investigator: J.M. Powers, Code 3234, Sponsoring Activity: NAVMAT 05B (CAPT Z. L. Newcomb), NUSC IED Program, Program Manager: Dr. K. M. Lima, Code 101. The authors are located at the Naval Underwater Systems Center, New London, CT 06320. This is the text of paper G9 delivered at the 109th Meeting of the Acoustical Society of America, held at the University of Texas, Austin, TX, 8-12 April 1985.

I. INTRODUCTION

This paper describes work we've been doing to make broadband, ultrasonic hydrophones out of piezoelectric poly(vinylidene flouride), or PVDF, for short. Up until recently, virtually all hydrophones have been made out of materials that are acoustically hard compared to water. That is, the mechanical impedance, seen looking into the hydrophone from the water medium, was necessarily large compared to water's impedance. For example, the characteristic impedance of lead zirconate-titanate is about twenty times the rho-cee of water. Lithium sulfate, another commonly-used hydrophone-element crystal, has about 7 1/2 times water's impedance. It's only with the advent of piezoelectric PVDF, a polymer plastic material, that the characteristic impedance for hydrophone element materials has even become close to water's rho-cee. Nonvoided PVDF has an impedance about twice that of water. More recently, voided PVDF has become available for use in hydrophones, and the voided material can actually be made to match the impedance of water. This means that we now have a rho-cee piezoelectric material which can be combined with rho-cee window materials to produce a rho-cee hydrophone.

II. THEORY

We will be talking about hydrophones that at high frequencies, when the transverse dimensions are more than a wavelength or so across, operate in the thickness mode. For a normally-incident sound wave, indicated in Figure 1a as having amplitude p_i, the motion of the piezoelectric plate is all in the thickness, or poled, direction. If the thickness is denoted by ℓ, and the density and sound speed by ρ and c for the water medium and ρ_o and c_o for the piezoelectric crystal, we obtain the free-field sensitivity, denoted as the ratio of e, the output voltage, to the incident pressure, p_i. In this expression for the sensitivity, h_{33} is the appropriate piezoelectric constant, m is the ratio of the medium and crystal characteristic impedances, and psi is 2π times the number of wavelengths in the thickness direction.

Figure 1b is a plot of the sensitivity expression for two different values of the impedance ratio, m. The solid curve is for a hard element with m=10, that is, the element impedance is ten times water's rho-cee, while the dashed curve is for m=1, in other words the impedance-matched case. This is a plot of sensitivity versus frequency, but we've indicated along the frequency axis where the half-wave resonances occur, that is the first resonance peak for the solid curve occurs when the piezoelectric element is one-half wavelength thick. Subsequent peaks occur at three, five, and seven half wavelenths, whereas you get a null in response whenever the element is an integral number of wavelengths in thickness. The resonances you see for the mismatched hydrophone are simply the result of multiple internal reflections forming standing waves inside the element. They occur because of the discontinuity in impedance at the element boundaries. On the other hand, if we match the impedance at the boundaries, there are no internal reflections and only a traveling

wave inside the element. The response, as shown by the dashed line, becomes a sin x over x curve which rolls off the way it does because of integration of the traveling wave over the thickness of the element. You might wonder why we even care what the response does at these frequencies that are higher than the useful band where the hydrophone response is flat. The problem is that, in many situations, there is a small amount of spurious high harmonic content that falls near the first resonance, and because the response at the peak is so much higher than the flat part of the curve, namely, 20 log of (2/) times the impedance ratio higher, you get a distorted output from the hydrophone.

Figure 2 is an illustration of what can happen. This is the output of an LC-5 hydrophone[1] to a 60-kHz high-amplitude underwater sound wave. Three different levels are shown. At the two lower levels, the hydrophone output is presumably a good indication of what is propagating in the water, but at the highest level, the wavefronts are steep enough to contain appreciable components near the 600 kHz resonance of this particular hydrophone, and so you get the ringing oscillation shown.

If we say that resonance peaks are caused by internal reflections within the hydrophone element, we can also talk about the effect of external reflections at the face of the element. At very low frequencies, the incident pressure wave diffracts around the hydrophone so that the pressure at the element face is equal to the free field pressure. Here we say that the diffraction constant is unity, that is zero dB on the plot of Fig. 3 at the low ka end. However, at high frequencies, a hard hydrophone will act like a rigid wall and the face pressure becomes double the incident value. This means that the diffraction factor is 6 dB, that is, the high frequency response is 6 dB higher than the low frequency response. This is shown in the upper plot of Figure 3. These plots are taken from a paper[2] by Ted Henriquez and show the diffraction factor for a circular piston at normal incidence as well as a cylinder and a sphere as a function of ka, the wave number-radius product. At any rate we can expect the sensitivity of a hard thickness-mode hydrophone to vary by 6 dB from the low to high frequency end of its band because of the diffracted wave created by reflection from the element. On the other hand, if we make an element whose characteristic impedance matches water's rho-cee, we should be able to drastically reduce this effect, because there should be very little contribution from the diffracted wave, since the plane-wave reflection coefficient, at least, has gone to zero.

The Underwater Sound Reference Division's E27 standard transducer[3] is often used as a hydrophone over the 50-to-500 kHz frequency range. It consists of seven PZT thickness-mode disks, wired in parallel and mounted to form a planar array eleven millimeters in overall diameter. The PZT disks are backed with corprene. A typical receiving sensitivity is shown in Figure 4. It illustrates both of the features we have discussed. There is a half-wave resonance peak at about 650 kHz that stands about 15 dB above the low-frequency

response. There is also a gradual increase in response from about 100 kHz up to about 500 kHz which is probably due to the diffraction factor effect. If you want to make a thickness-mode hydrophone out of acoustically hard piezoelectric material, these effects are difficult to avoid, at least in this frequency range. It should be noted that in the medical ultrasonics range, above 1 MHz, it's possible to operate entirely in the pressure doubling regime so that the diffraction factor no longer varies with frequency. One can also manage to find damping material to control the resonance peak at megahertz frequencies.

Our approach is to use piezoelectric PVDF which has been especially fabricated at Thorn EMI to match water's rho-cee product. The sound speed was measured after trial stretching by an immersion technique in which the propagation phase shift was measured with and without the PVDF inserted in the acoustic path. The hydrophone element is indicated in Figure 5 by the number 1. It's, potted inside a rho-cee window material, indicated as number 10. In our case, we used a polyurethane, Uralite 3138, which we know to be a good acoustic match to water.[4] Unfortunately, PVDF has a low permittivity, on the order of 10, and so to minimize the coupling loss we need to feed the output into a nearby preamplifier (item number 5), which, of course, cannot be made of rho-cee material. Then the trick is to place the preamp far enough away from the element to reduce any pressure waves scattered into the element and near enough to keep the coupling loss small.

The computed sensitivities for rho-cee hydrophones having various element thicknesses are shown in Figure 6. The tradeoff between sensitivity and bandwidth can be seen in the figure. In other words, one can have more sensitivity by going to a thicker element but less bandwidth will be the result.

III. Experiment

One of the hydrophones we built (designated Mk V) is shown in Figure 7. Thorn EMI rho-cee element material (Sample No. 2317C, ρ_o=1460 kg/m^3, c_o=975 m/s) was used. The element is in the lower left part of the figure. The element thickness was about 0.33 mm, and the active area about 1.9 cm square. The polyurethane potting material is very flexible, having a Shore A hardness of only 25, and we needed some kind of handle to hold the hydrophone so we could control its angular orientation. Therefore we compromised on the rho-cee matching as soon as we got above the element and used a fiberglass/epoxy rod as a stiffening member. That can be seen toward the upper part of the figure. We took pains to eliminate air from the wires and the potting material. This was done by injecting the urethane under vacuum in a process developed by John Redding of our chemistry laboratory. The hydrophones were constructed by Tony Corcella. All the hydrophones were provided with connectors like the one shown at the upper right so that they could be used with the same preamplifier.

The preamplifier is shown in Figure 8, with the mating connector toward the right. Bill Konrad designed the preamp around an NE531 operational amplifier chip which was followed by an emitter follower which drove the 50-ohm load presented by the triaxial 50-ohm cable terminated at the dry end with a 50-ohm resistor. Bill Clay did the breadboarding and construction of the preamp. It provided 20.5 dB of gain and was flat to about 900 kHz.

IV. Results and Conclusion

The solid line of Figure 9 is the measured sensitivity of the Mk V hydrophone as obtained by Don McGrath and Dave Mitchell at the Underwater Sound Reference Division in Orlando. The dashed line is the computed plane-wave response with the h_{33} piezoelectric constant adjusted for best fit to the data. In other words, sensitivity measurements like this one provide the best means of determining h_{33}. Based on these results, h_{33} is about 3.8×10^8 volts per meter for this material. The shape of the measured response does not vary more than about 1 dB from the computed response, and this is gratifying.

Figure 10 shows the response for a second hydrophone (Mk VA) that was made from the same rho-cee element material. In this case, however, the cable capacitance was less and so the sensitivity was about 2 dB higher because of lower coupling loss. Here again the response was within plus or minus one dB of the computed plane wave response. As we tried to operate these hydrophones down to the kHz range, we ran into 60 Hz pickup problems because the elements are unshielded. Therefore we are presently working on a bilaminar element that should be self-shielding. Each half is going to have to be half as thick, however, to have the same frequency response and that means 6 dB less sensitivity.

V. References

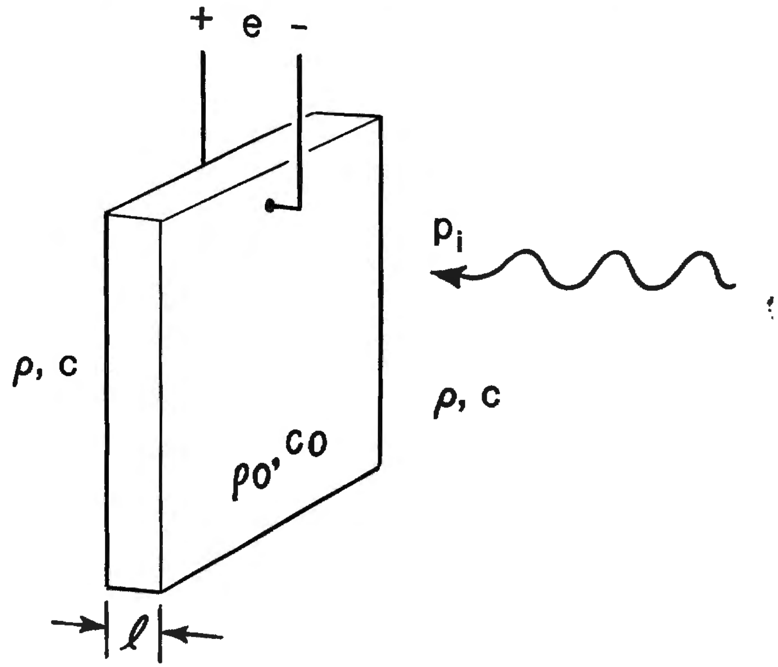
1. Product data sheets, Celesco Industries, Div. of the Susqehanna Corp., 7800 Deering Ave., Canoga Park, CA 92104.

2. T. A. Henriquez, "Diffraction Constants of Acoustic Transducers," J. Acoust. Soc. Am. 36, 267-269 (1964).

3. "Underwater Electroacoustic Standard Transducers," NRL/USRD Transducer Catalog (April, 1982).

4. J. Bantly, "Comparison Testing of Three Urethane Elastomers," NUSC Memorandum 3234:JWB:pbg (26 March 1984).

THICKNESS-MODE HYDROPHONE



$$\left|\frac{e}{p_i}\right| = \frac{h_{33}\ell}{\rho_0 c_0^2}\,\frac{2}{\psi}\sqrt{\frac{(1-\cos\psi)^2 + (m\sin\psi)^2}{((1+m^2)\sin\psi)^2 + (2m\cos\psi)^2}}$$

WHERE $\psi = \omega\ell/c_0$

h_{33} = PIEZOELECTRIC CONSTANT

$m = \rho c/\rho_0 c_0$

Fig. 1a. Sensitivity of thickness-mode hydrophone.

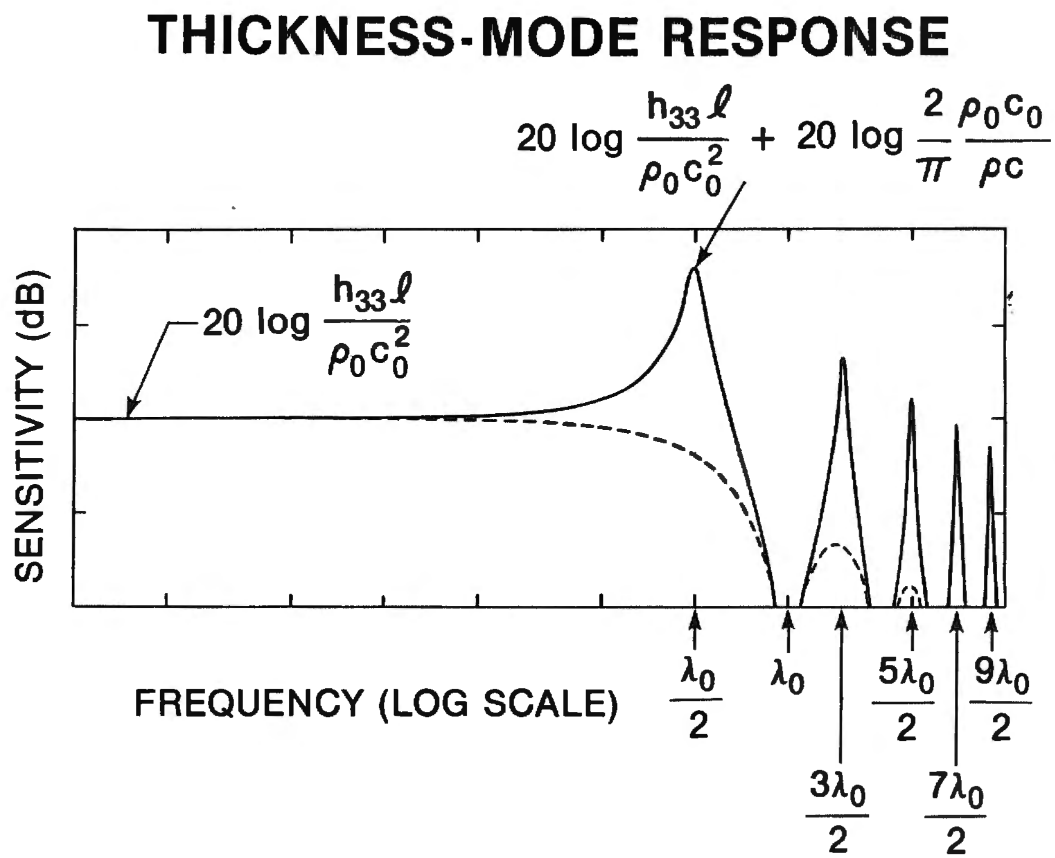


Fig. 1b. Sensitivity of thickness-mode hydrophone.

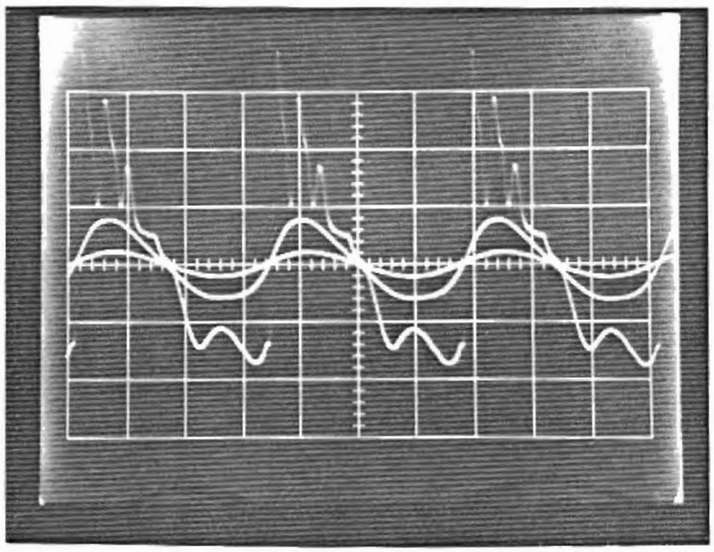


Fig. 2. Example of hydrophone ringing response to high-amplitude waveform. (Lower amplitudes do not cause ringing, because they do not involve harmonics near the hydrophone resonance.)

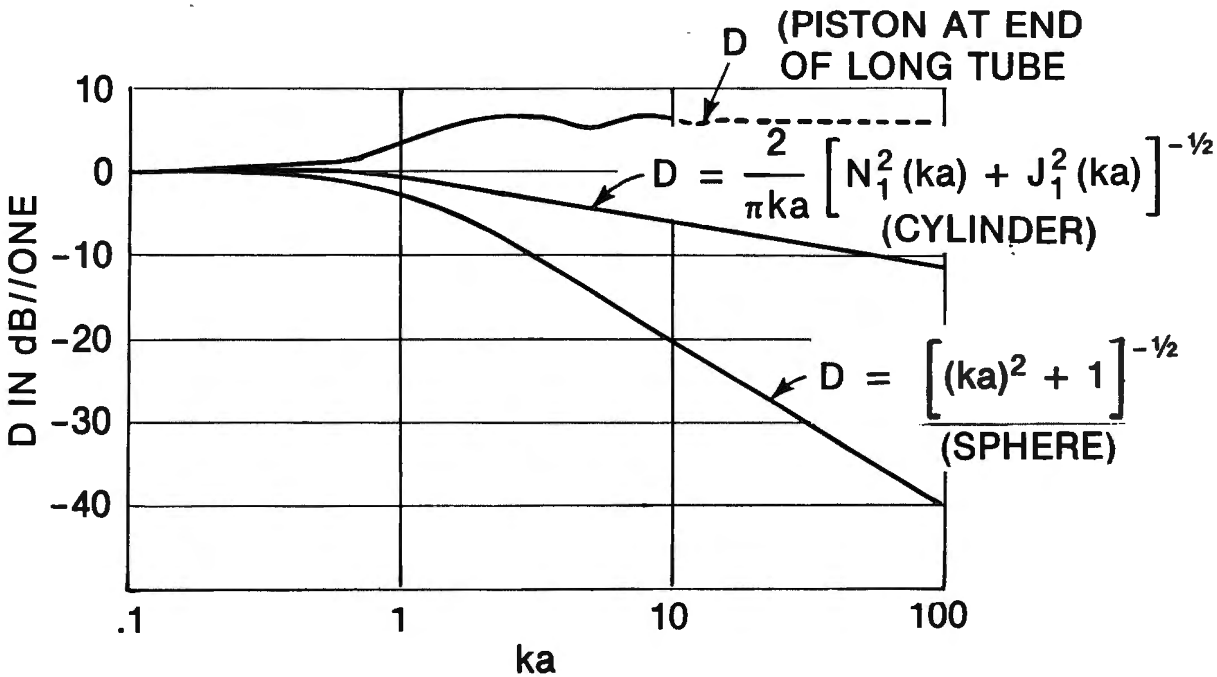


Fig. 3. Diffraction factor for 3 hydrophone configurations (after Ref. 2).

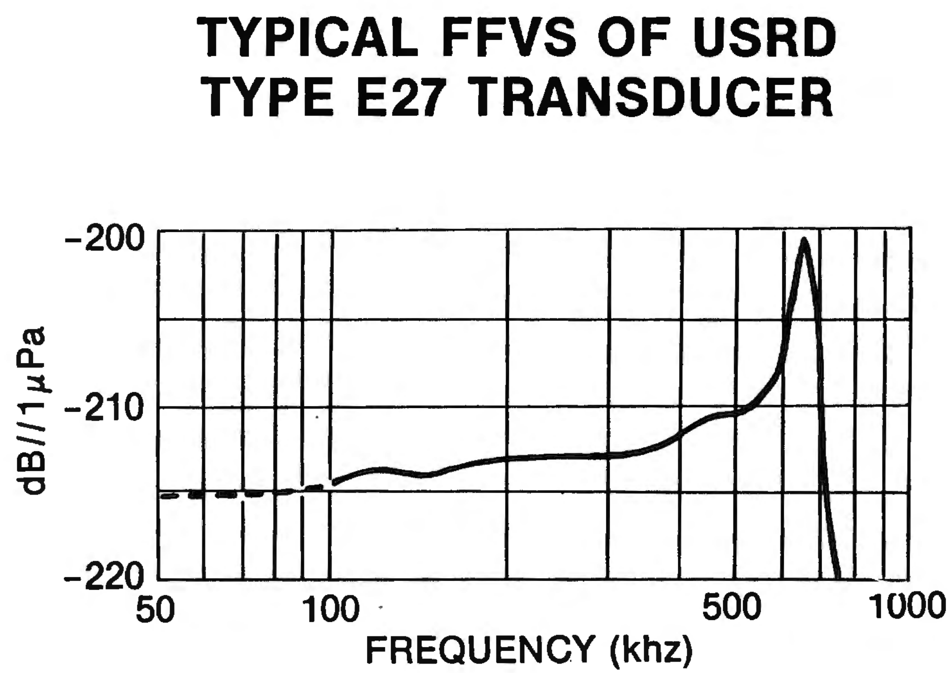


Fig. 4. Typical receiving sensitivity of USRD E27 hydrophone (after Ref. 3).

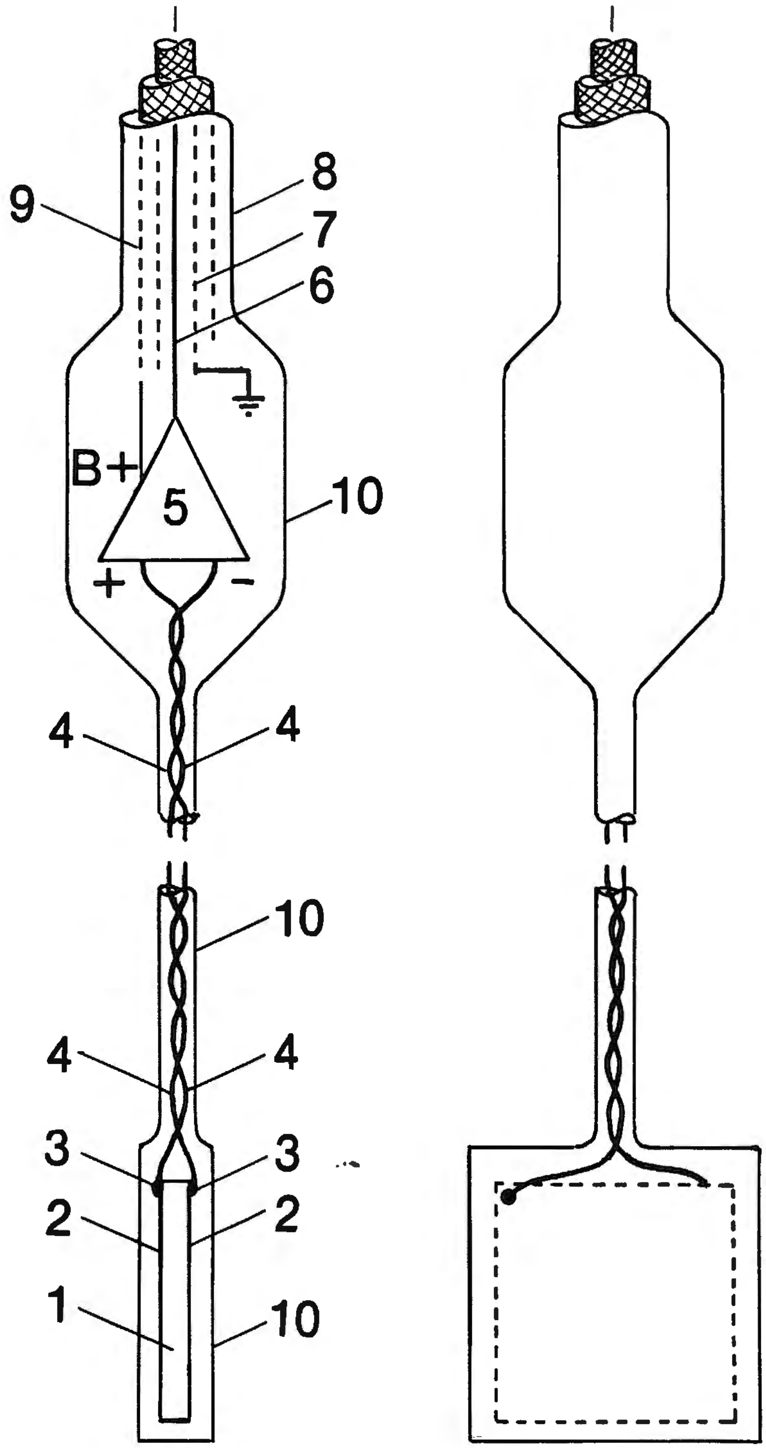


Fig. 5. Schematic drawing of rho-cee hydrophone.

RHO CEE HYDROPHONE SENSITIVITY

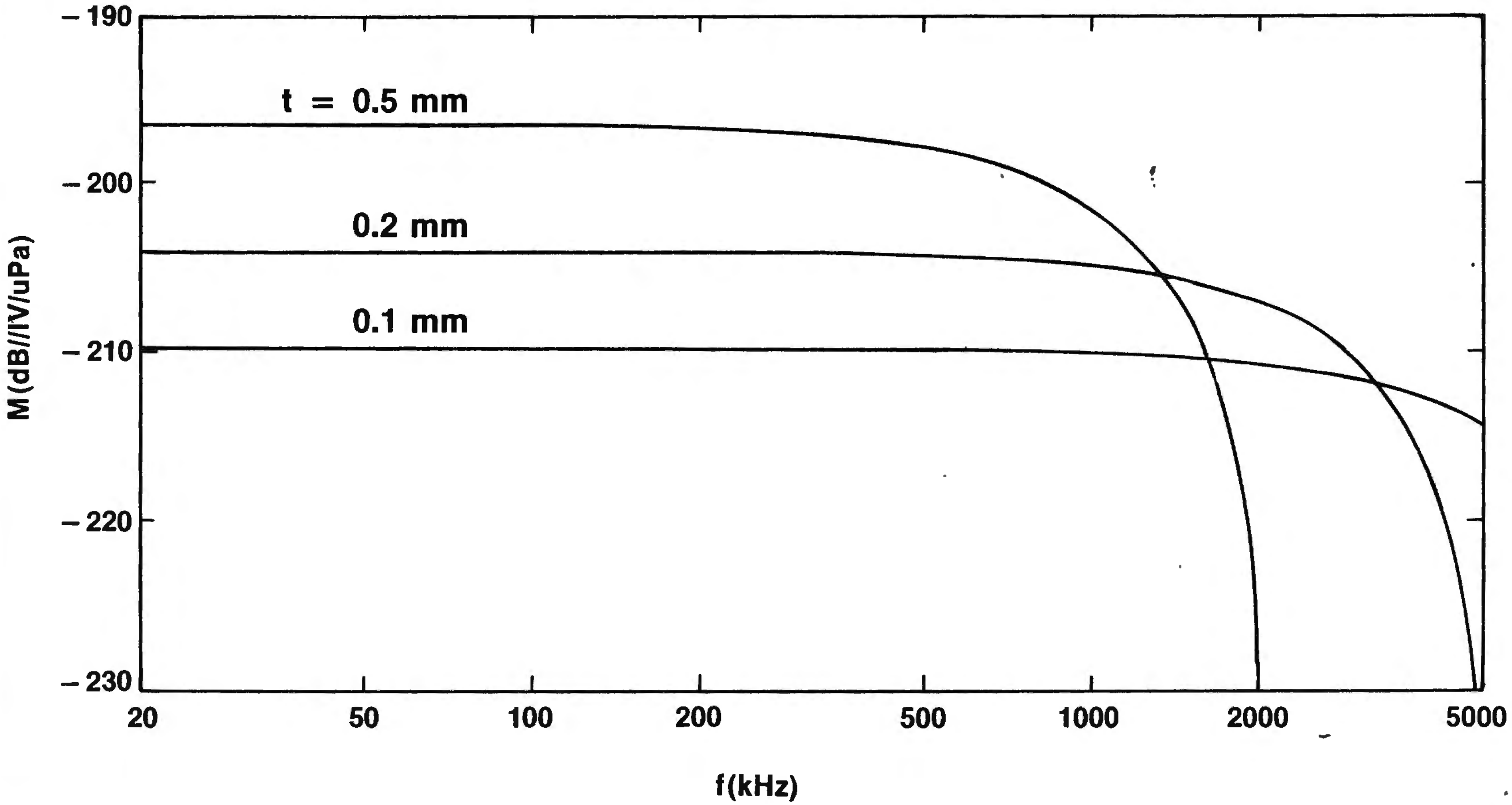


Fig. 6. Computed sensitivities, ideal rho-cee hydrophones of various element thicknesses.

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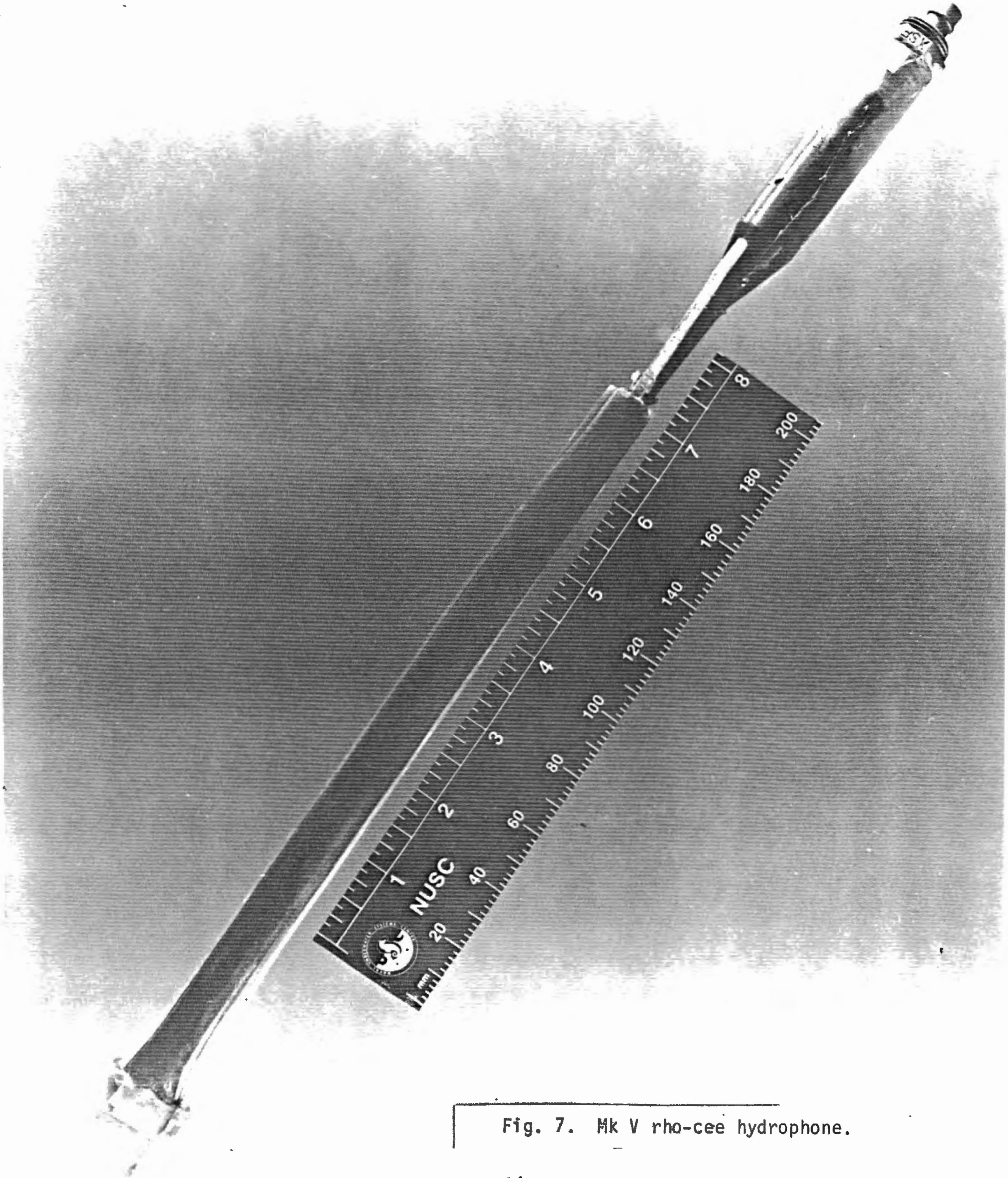

Fig. 7. Mk V rho-cee hydrophone.

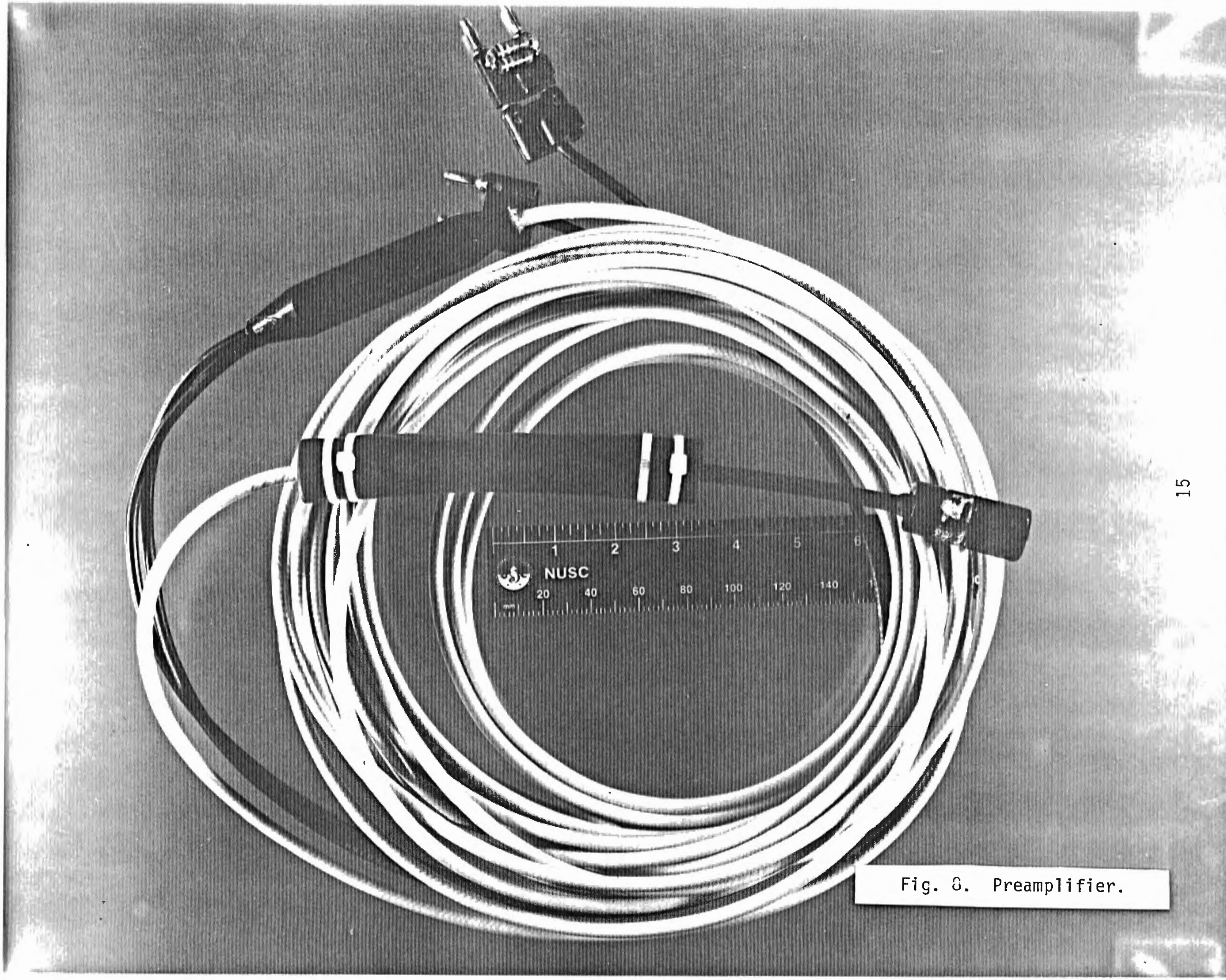

Fig. 8. Preamplifier.

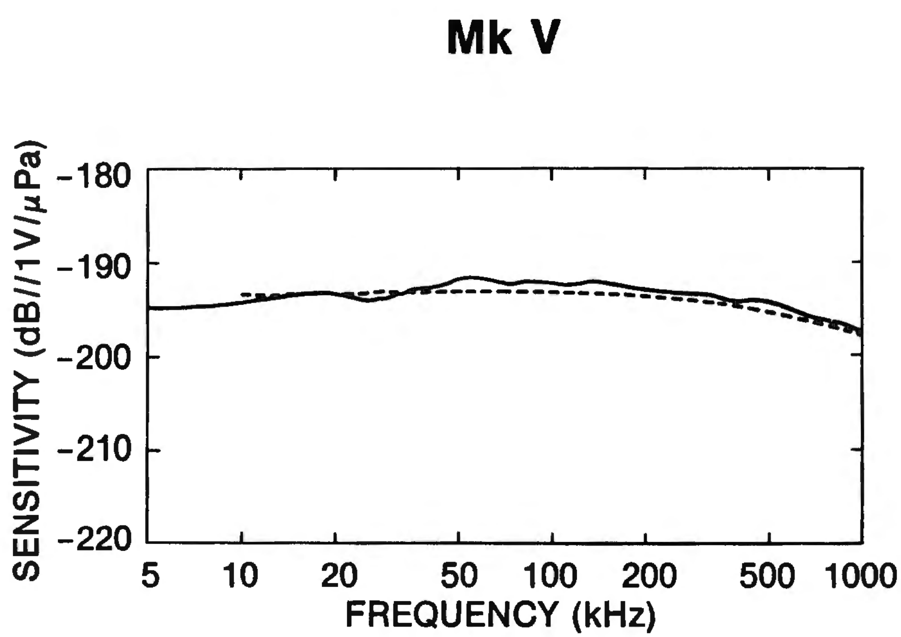

Fig. 9. Sensitivity of Mk V rho-cee hydrophone.

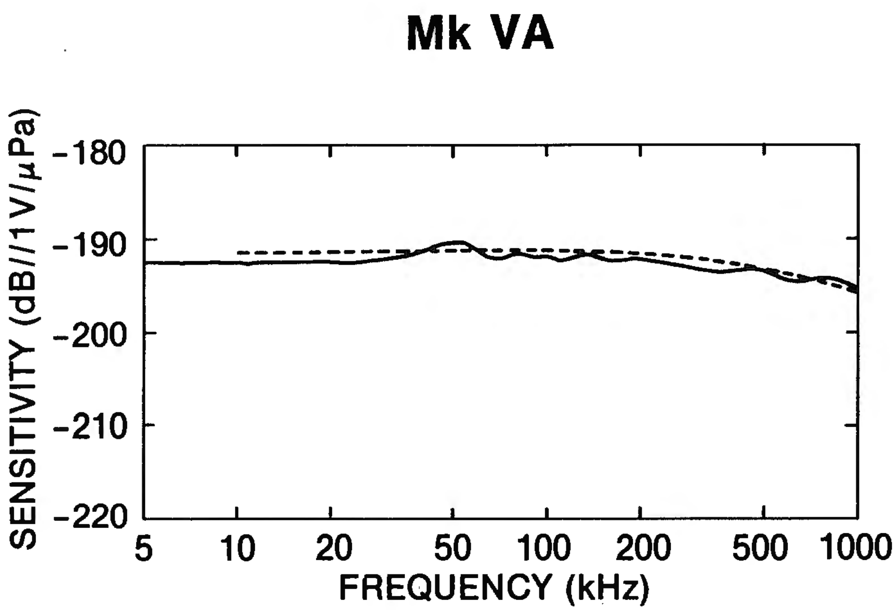

Fig 10. Sensitivity of Mk VA rho-cee hydrophone

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